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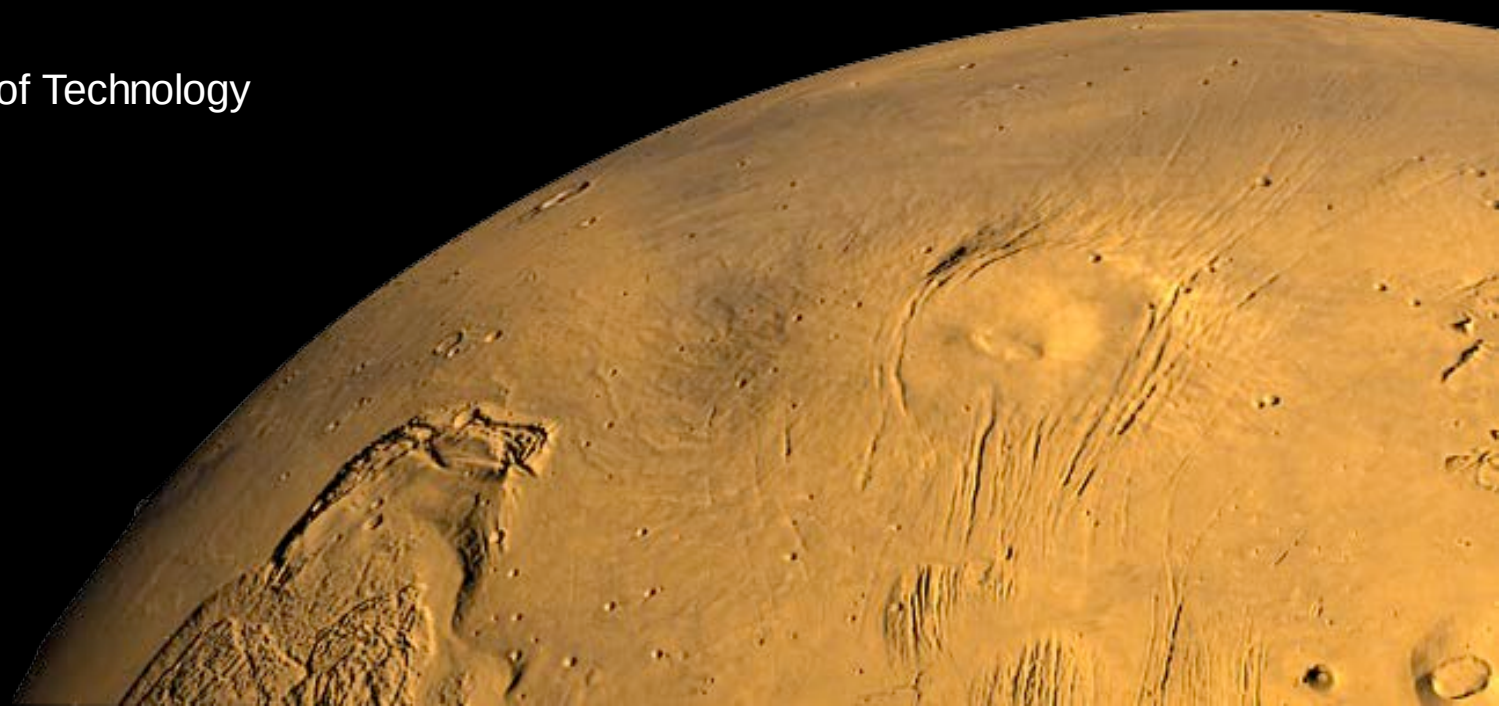
Emerging Technologies for Mars Exploration

Chad Edwards

Jet Propulsion Laboratory, California Institute of Technology

chad.edwards@jpl.nasa.gov

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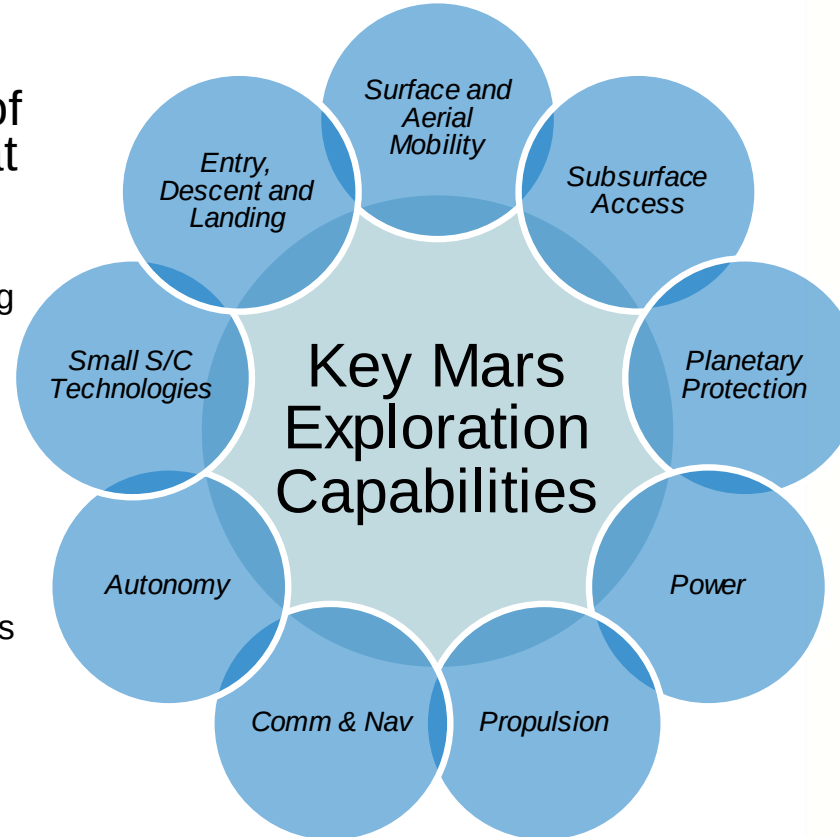


Agenda

- Introduction
- Selected Technology Areas
 - Enabling technologies for Mars Sample Return
 - Enhanced surface mobility
 - Access to the subsurface
 - Small spacecraft capabilities
- Summary

Introduction

- Mars exploration capabilities have progressed dramatically over more than two decades of continuous robotic presence at Mars
 - Orbital
 - High-bandwidth remote sensing
 - Landing site reconnaissance
 - Telecommunications relay infrastructure
 - Surface
 - Increased landed mass
 - Increased mobility
 - Improved landing accuracy
 - Enhanced sampling capabilities
- Addressing the next layer of Mars science questions will demand new exploration capabilities and associated technology investments over the coming decade



Emerging Capabilities for Mars Exploration

C. D. Edwards, Jr.¹, M. J. Amato², J. D. Baker¹, N. J. Barba¹, J. Balaram¹, E. J. Brandon¹, P. Briggs¹, B. D. Davis¹, J. C. Day¹, A. Freeman¹, M.R. Grover¹, G. S. Hubbard¹, D. B. Lavery², L. Mandrake¹, L. H. Matthies¹, G. Meirion-Griffith¹, M. M. Munk⁶, I. A. Nesnas¹, R. W. Obbard⁷, M. Ono¹, M. A. Peck⁸, V. Stamenković¹, S. A. Townes¹, T. G. Trenkle², E. Venkatapathy⁹, K. A. Zacny¹⁰

¹Jet Propulsion Laboratory, California Institute of Technology, ²NASA GSFC, ³NASA MSFC, ⁴Stanford University, ⁵NASA Headquarters, ⁶NASA LaRC, ⁷SETI Institute, ⁸The Johns Hopkins University Applied Physics Laboratory, ⁹NASA ARC, ¹⁰Honeybee Robotics

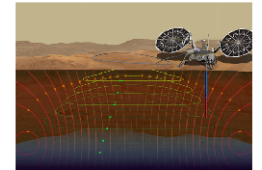
Contact: C. D. Edwards, Jr. (Jet Propulsion Laboratory, California Institute of Technology)
email: chad-edwards@jpl.nasa.gov, phone: 818.354.4408



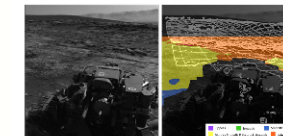
Artist concept of the Ingenuity Helicopter demo on Mars 2020



Field testing of the Axel Tethered Rover



Valkyrie subsurface mission concept



Onboard rover terrain classification for safe and energy-aware path planning



Watson Deep Drill under test in Greenland

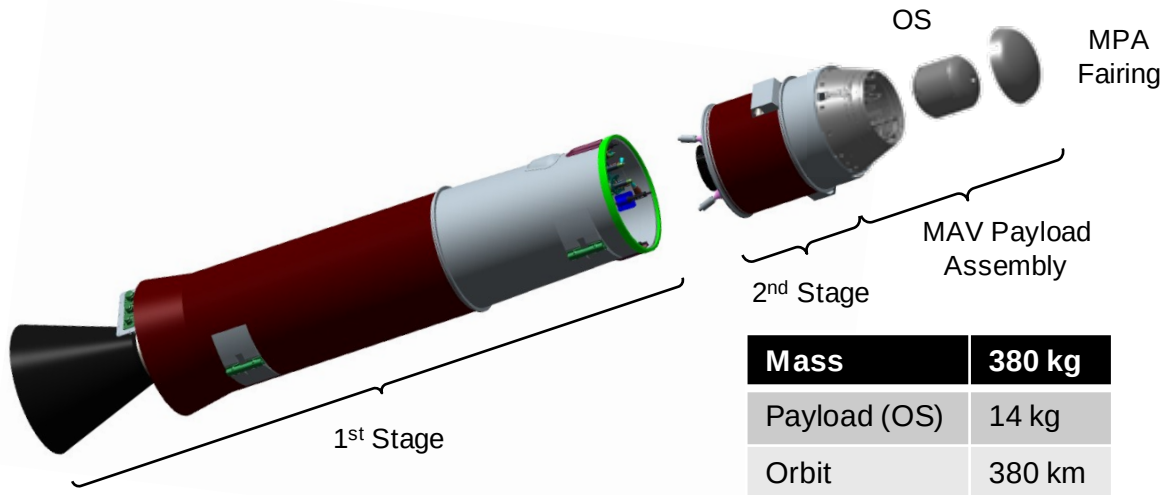


Artist concept of the MSR Mars Ascent Vehicle launch

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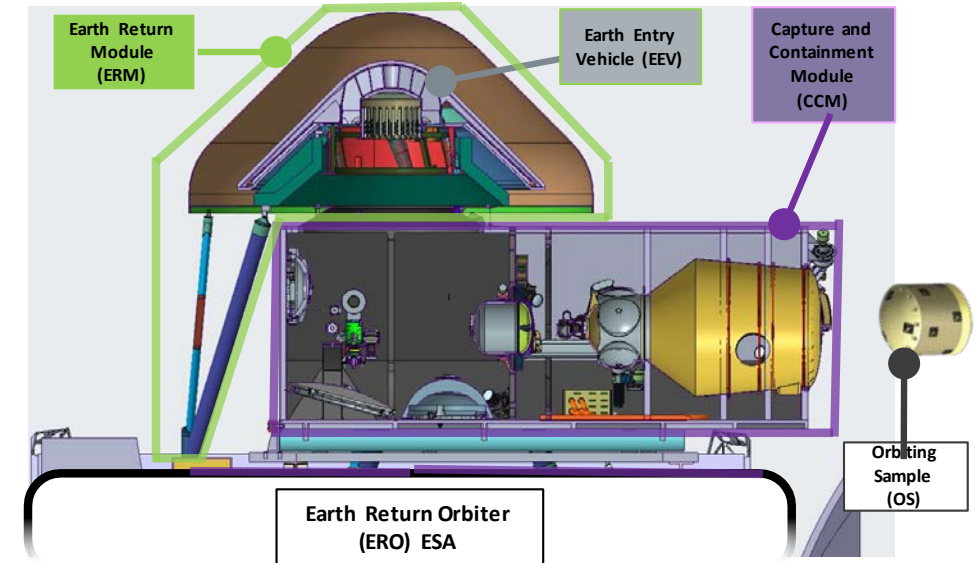
Enabling Technologies for Mars Sample Return

Mars Ascent Vehicle Baseline Design



- Launch Orbiting Sample (OS) into 380 km circular orbit
- Two-stage (guided, unguided) solid motor vehicle
 - 1st-stage electromechanical Thrust Vector Control
 - 2nd-stage spin/de-spin motors
 - Monoprop Reaction Control System
- MAV Payload Assembly (MPA)
 - Ejectable fairing
 - Orbiting Sample (OS)

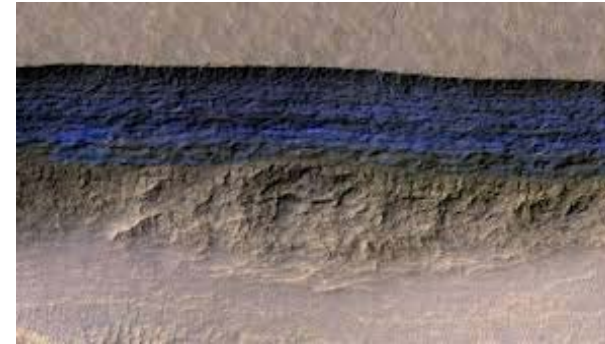
Planetary Protection/Containment Assurance



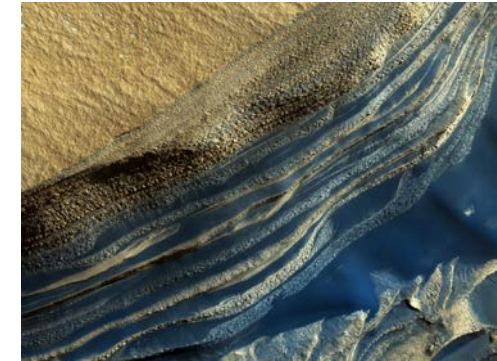
- Capture, Containment and Return System (CCRS) Concept
 - Capture and Containment Module
 - Capture OS in Mars orbit, constrain & orient
 - Break-the-Chain and Containment Assurance
 - Transfer contained OS to Earth Entry Vehicle
 - Earth Return Module
 - MMOD protection
 - Earth Entry Vehicle for robust delivery to landing site

Access to New Regions on Mars

- Mars in situ missions to date have been limited to surface and near-surface (<10 cm) access in regions compatible with current lander/rover capabilities
- Next phases of Mars exploration can be enabled by capabilities for accessing new regions
 - Extended mobility
 - Accessing diverse geologic environments
 - Extreme terrains
 - Gullies and RSLs
 - Exposed scarps
 - Polar Layered Deposits
 - Subsurface
 - Sounding for subsurface groundwater
 - Drilling to depths relevant for determining modern-day subsurface habitability



Exposed Ice Scarps



Polar Layered Deposits



Deep Subsurface TEM
Sounding & Drilling Concepts



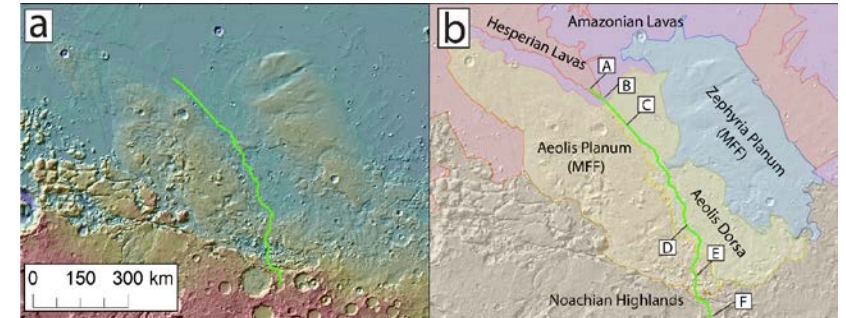
Recurring Slope Lineae

Extended Mobility - Long-Range Rovers

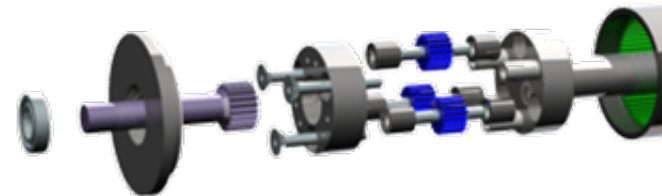
- MEPAG and MASWG both advocate exploring the diversity of Mars surface environments
- Options
 - Multi-rovers – high cost of multiple vehicles and EDL systems
 - Long-range rover – need to achieve drive distance capabilities of 100-1000 km to span distinct geologic units
- Prior capabilities:

	Total Drive (km)	Duration (yr)	Avg Rate (km/yr)	Max Drive Sol (m)
Spirit	7.7	6.2	1.2	124
Opportunity	45	14	3.2	220
Curiosity	24.1	8.4	2.9	142

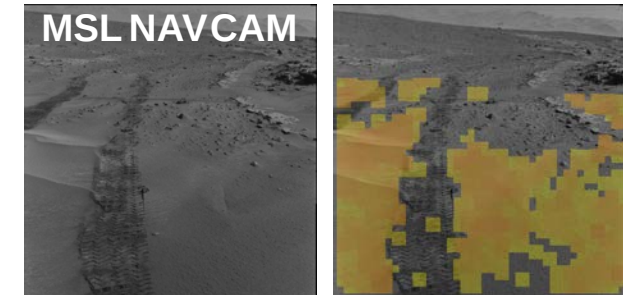
- Long-range mobility target: >1 km/sol drive capability
 - Could achieve >350 km/Mars year, assuming 50% drive sols
- Key technology needs for achieving long-range mobility:
 - Heaterless, high-speed mobility actuators (30 cm/sec drive speed) employing bulk metallic glass gears
 - Onboard autonomy enabling map-based position estimation, terrain classification, and rapid recovery from driving faults
 - High-performance, low-SWaP avionics



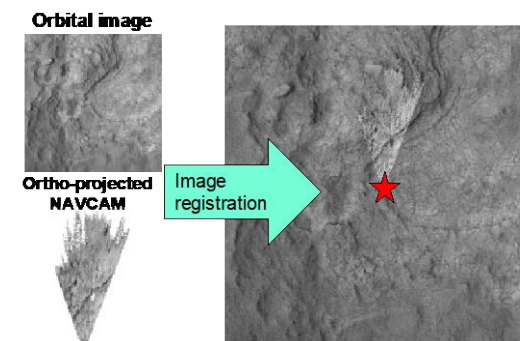
Medusae Fossae Formation traverse example (825 km)



Bulk metallic glass gears in planetary gearboxes



Deep learning-based terrain classification



Rover Map-based position estimation



Long-range autonomous drive demo in JPL Arroyo

Axel Rover Concept

- Tethered mobility system enables access to slopes $>25^\circ$
- $>100\text{m}$ rappel distance
- Instrument bays in each wheel can accommodate multiple instrument payloads
- Key technical challenges:
 - Robust tether management
 - Instrument accommodation and deployment
 - Autonomous tethered navigation in complex slope environments

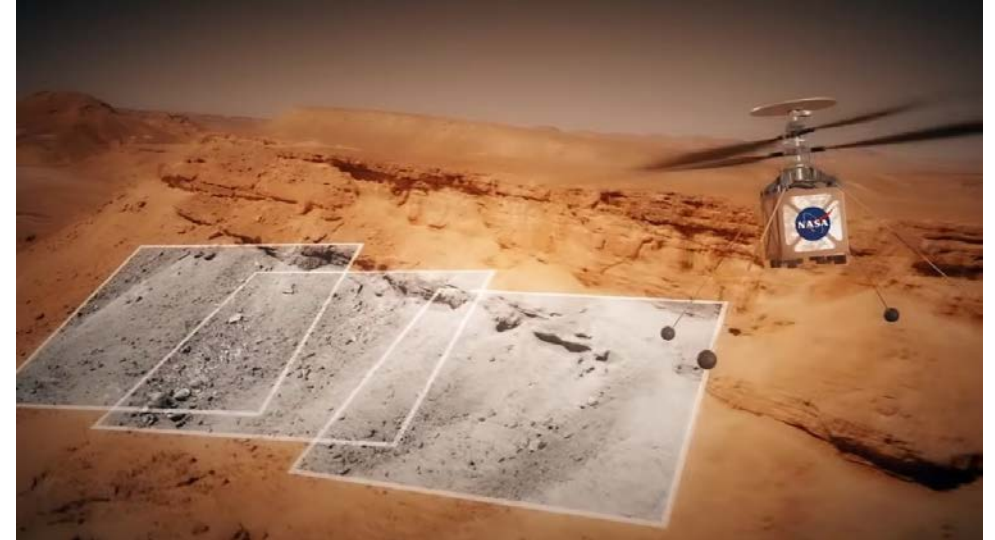


Issa Nesnas/JPL



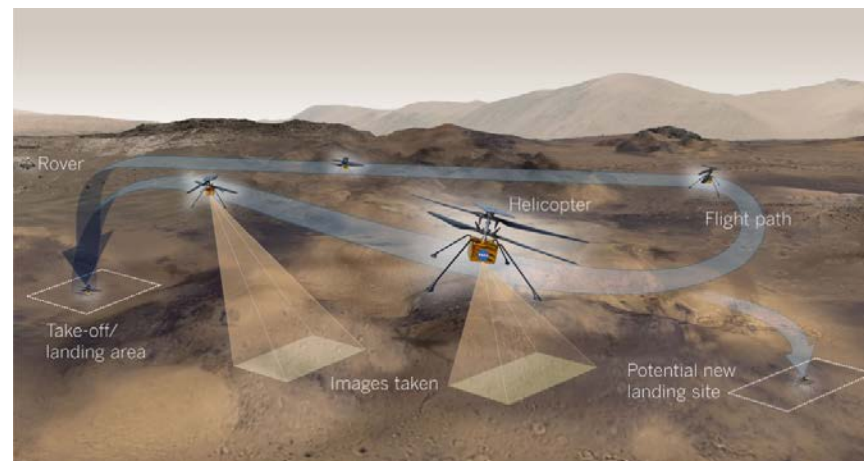
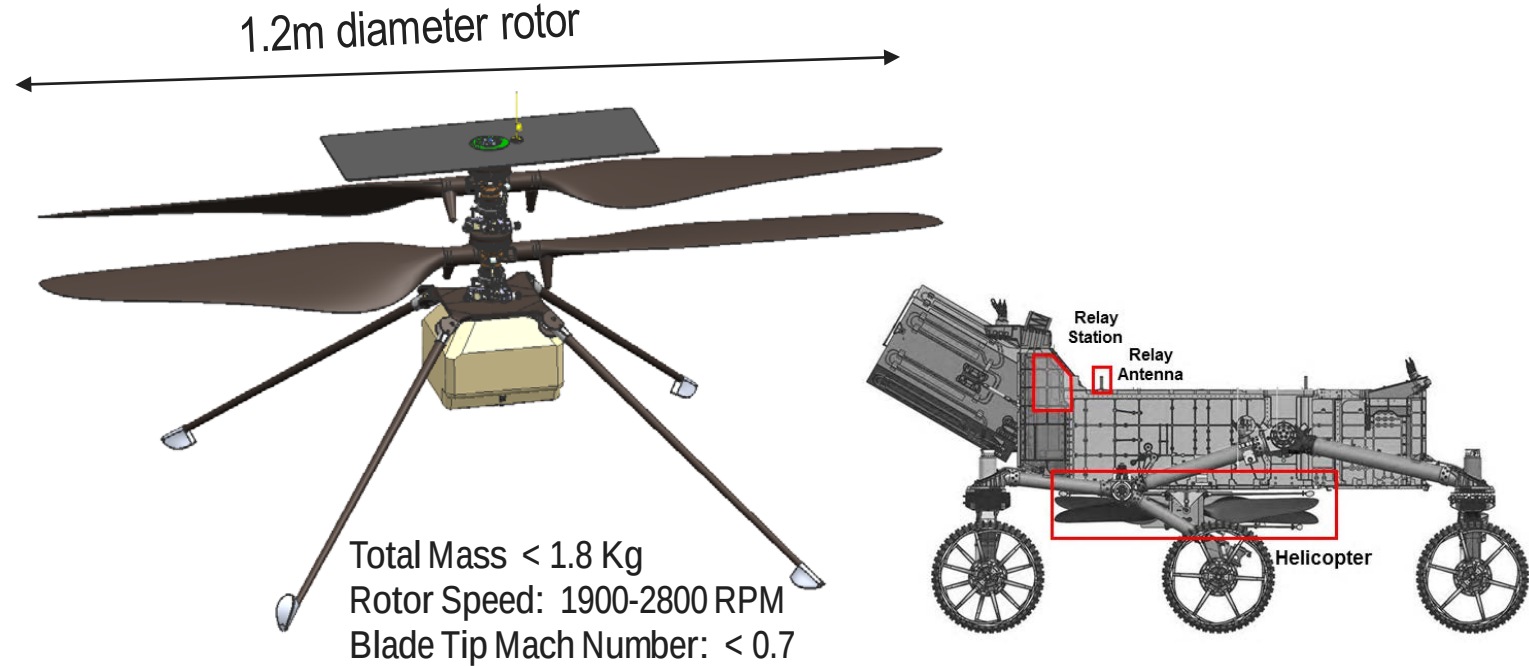
Mars Rotorcraft Concept

- Mars rotorcraft offer a compelling new platform for *in situ* exploration
 - Mesoscale access
 - Greater range than rovers
 - Better resolution than orbiters
 - Extreme terrain access
 - Slopes, gullies, scarps, ...
 - Atmospheric boundary layer access
- Key challenges
 - Extremely low Mars atmospheric density
 - Autonomous flight navigation and landing



Ingenuity Mars Helicopter Technology Demonstration

- Solar powered - up to one 90-second flight per day
- Flight Range up to 300 m
- Heights up to 10 m
- Autonomous flight & landing
- Blade design for thin atmosphere
- Able to survive cold Martian nights

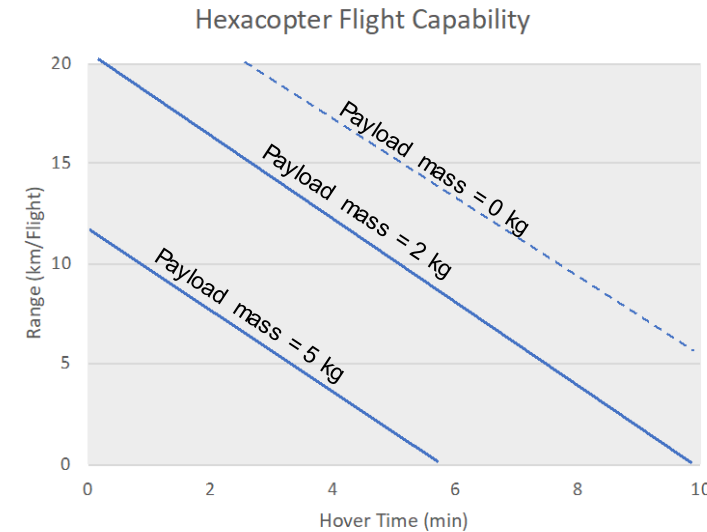


Mars Science Helicopter Concept

- JPL & ARC are currently studying how to move beyond MHTD to a fully capable Mars Science Helicopter platform
- Reference Design
 - Up to 30 kg system mass
 - Hexacopter configuration (also studying co-axial option)
 - Advanced navigation capabilities
 - Autonomous Landing Site Detection
 - All-Terrain Navigation
 - Long-range Map-based Navigation
 - Assessing mid-air delivery system for low-cost mission concepts not requiring a base lander
 - Key technology needs:
 - Aerodynamic design & modeling
 - High specific power & energy batteries
 - Low-SWaP avionics and instruments



Mars Science Helicopter Concept

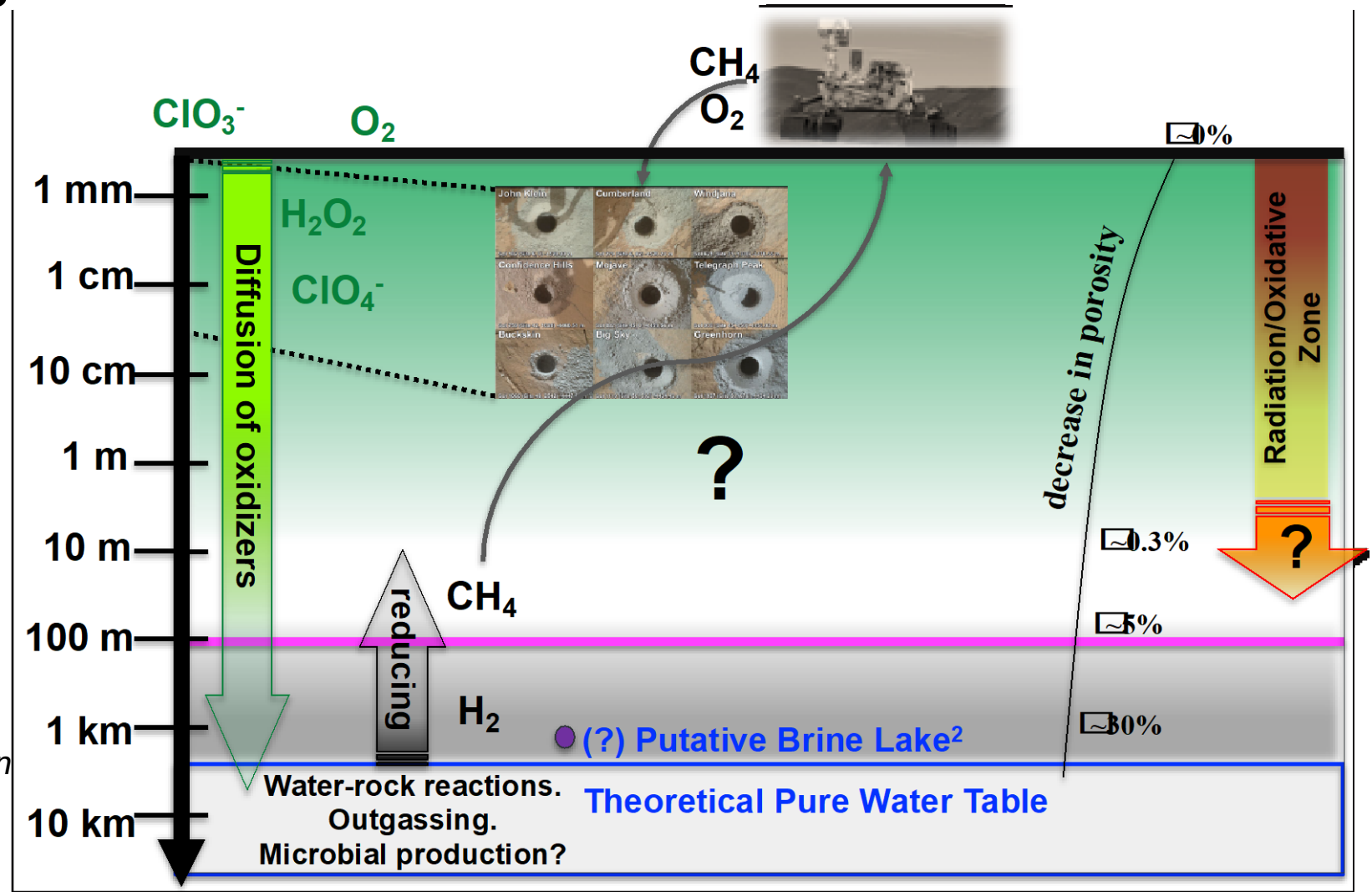


Field testing of Earth-based demonstrator UAV

Subsurface Access

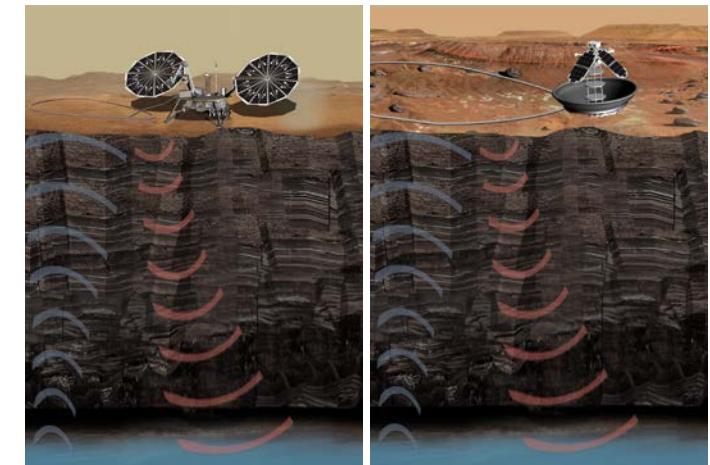
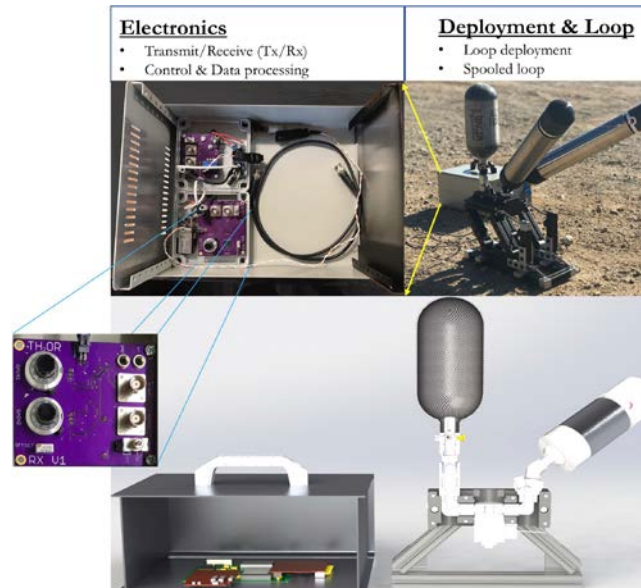
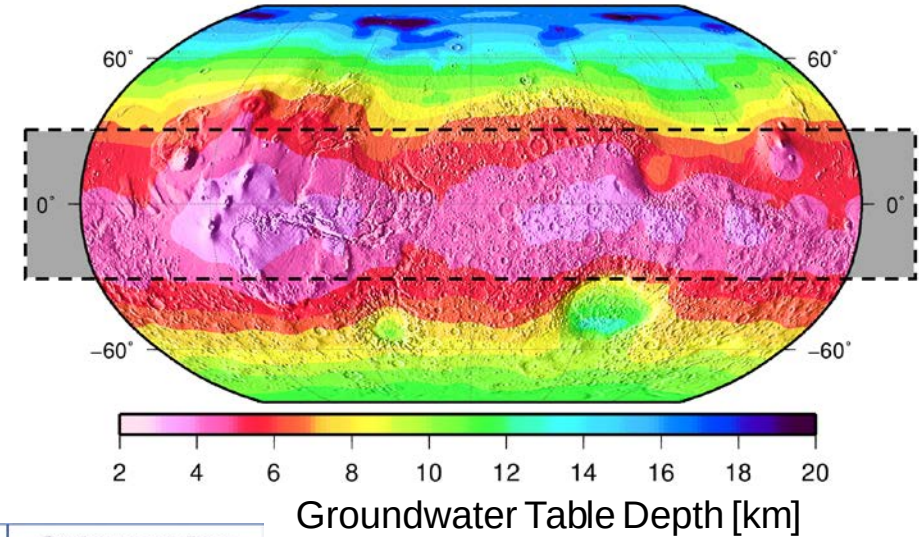
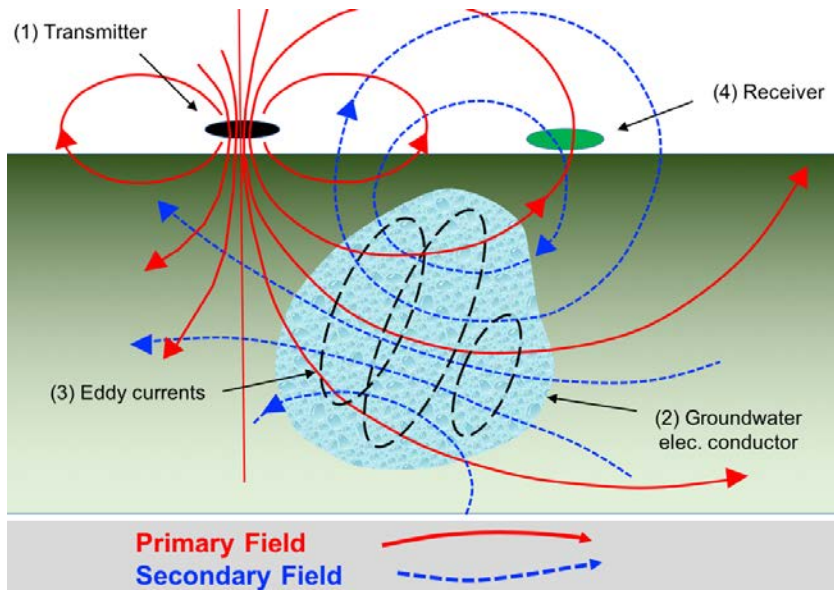
- The Martian subsurface is a prime target for astrobiology
 - Shielded from surface radiation environment
 - Potential for liquid water aquifers
 - Potential modern habitable environment and abode for extant life

See the PSADS White Paper “Deep Trek: Science of Subsurface Habitability & Life on Mars - A Window into Subsurface Life in the Solar System”, V. Stamenkovic, K. Lynch, P. Boston, J. Tarnas, et al.)



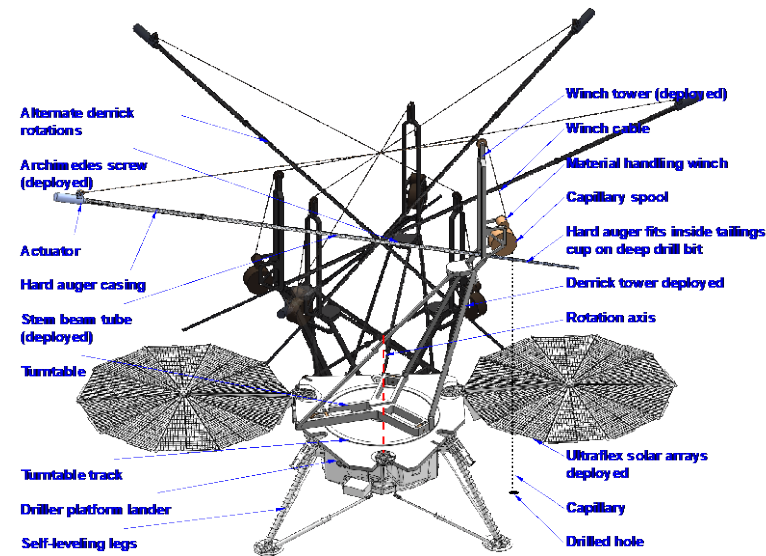
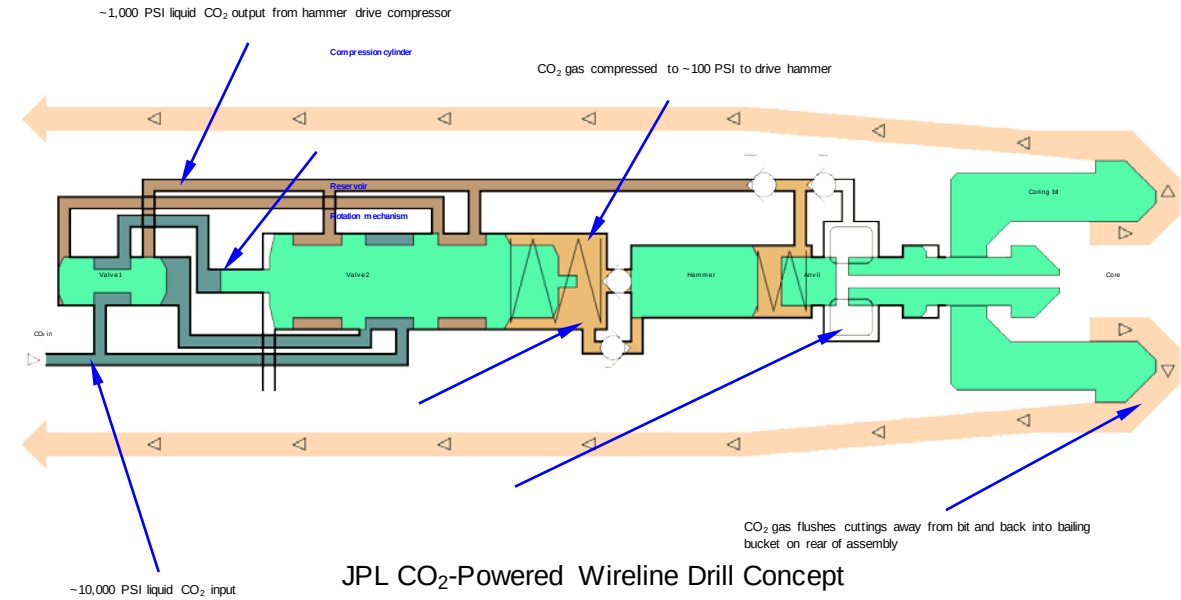
Remote Sensing – Transient Electromagnetic Sounding

- Transient Electro-Magnetic (TEM) sounding provides capability of detecting and characterizing Martian groundwater
 - TH₂OR (Transmissive H₂O Reconnaissance) instrument concept in development at JPL

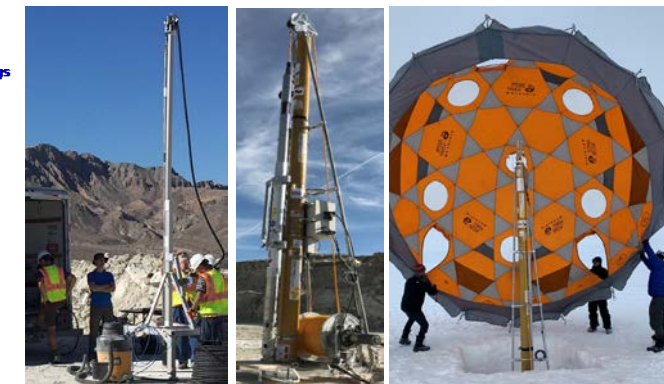


Deep Drilling

- Wireline drill concept for accessing depths of 10s-100s m with low mass and power
- Leverage demonstrated, highly reliable, terrestrial rotary-percussive drill technology, with key innovations for use on Mars:
 - Reduced drill bit diameter (3 cm)
 - Reduced mass and power (<100 kg, <100 W)
 - Autonomous operations
 - Use of compressed liquid CO₂ (extracted from Mars atmosphere) to power drill
 - Same CO₂ – upon vaporizing – serves to flush cuttings from borehole into bailing bucket
 - Sub-mm fused silica capillary serves as wireline and also as conduit for pressurized CO₂
 - All downhole parts rated for > 350°C, enabling straightforward sterilization
- Instrument options
 - Borehole fiber for UV/Raman spectroscopy
 - Sample delivery to lander deck for TLS for isotopologue analysis, or more sophisticated organics analyzers (e.g., MOMA, SAM)



Drilling Lander Configuration
(Artist's Concept)



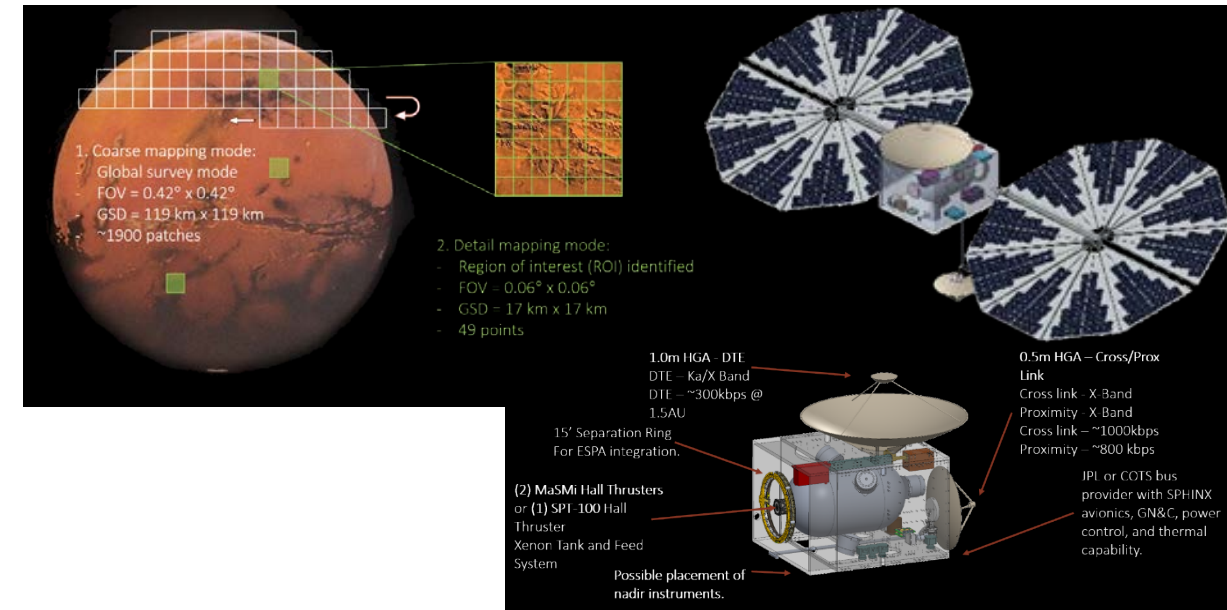
Honeybee Wireline Drill Prototypes
Courtesy: K. Zacny

Low-Cost Access to Mars

- Small Mars spacecraft missions can achieve compelling science at a fraction of Discovery costs
 - Leverage emerging commercial Cubesat/Smallsat spacecraft subsystems
 - Formulate science mission concepts with focused instrument payload suite
 - Utilize low-cost methods to deliver small spacecraft to Mars
 - Piggyback on Mars-bound mission primary mission
 - Rideshare to GTO or Earth escape
 - Launch on new class of small low-cost LVs (e.g., Firefly, Relativity)
 - Mars small spacecraft missions can be further enabled by improved relay capabilities to support both landed and orbiting small spacecraft

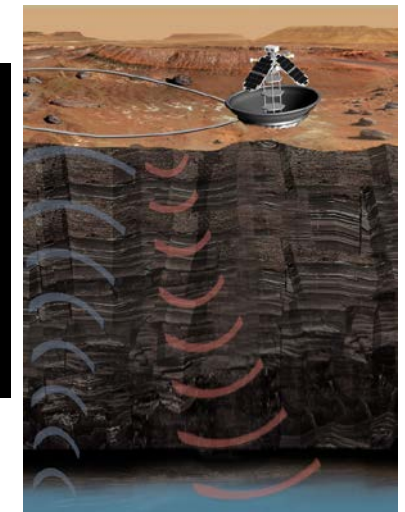
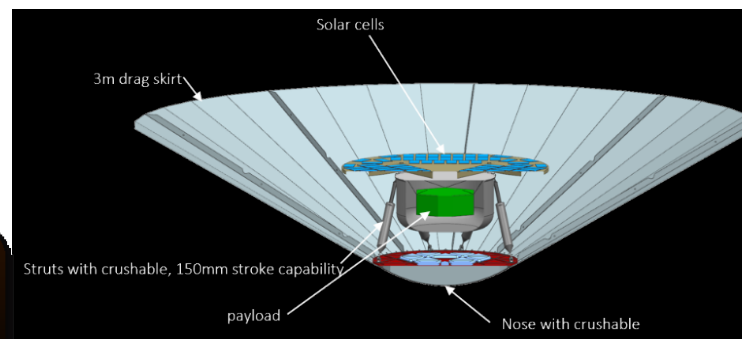
AREO TGL: High Orbit Concept Case Study

Areostationary Trace Gas Localizer



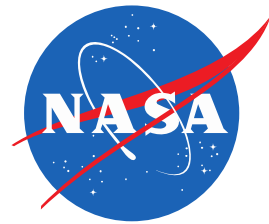
Surface/Subsurface Concept Case Study

SHIELD Impact Lander Concept



Summary

- New capabilities are needed to enable the next era of Mars exploration
- Examples presented here:
 - Key MSR technologies
 - Mars Ascent Vehicle
 - Back Planetary Protection/Containment Assurance
 - Enhanced surface access
 - Rotorcraft
 - Tethered rovers
 - Long-range rovers
 - Access to the Martian subsurface
 - TEM remote sensing
 - Deep drilling
 - Small spacecraft missions
 - Cost-effective opportunities to continue compelling Mars science in parallel with Mars Sample Return
- Focused NASA technology investments will be essential to establish these capabilities



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